II International Conference on Particle-based Methods – Fundamentals and Applications
PARTICLES 2011
E. Oñate and D.R.J. Owen (Eds)

DEM SIMULATIONS OF SOIL-PILE INTERFACE UNDER STATIC AND CYCLIC LOADING

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Key words: DEM, soil-pile interface, CNL and CNS tests, static and cyclic loading

ABSTRACT: In this study, Discrete Element Method (DEM) was used to simulate interface direct shear tests for both constant normal load (CNL) and constant normal stiffness (CNS) conditions. The model was calibrated and validated using laboratory data. Simulations were made for both static and cyclic tests for different amplitudes at normal stress levels ranging from 100kPa to 400kPa on sand having relative density of 50%. No major difference was observed between static CNS and CNL tests for shear stress behaviour. However, a decrease in normal stress was observed in CNS tests which were evident from the imposed boundary conditions. In cyclic CNS tests, degradation of shear stress was observed for higher displacement amplitudes. Shear band thickness was measured from rotation diagrams and was observed to be 5 to 10 times D_{50} for all the tests.

1 INTRODUCTION

Direct shear apparatus is often used in the laboratory to study soil-pile interface behaviour. The normal load boundary condition employed in direct shear apparatus can be expressed as follows:

$$\sigma_n = \sigma_{n0} - K\Delta z \tag{1}$$

where, σ_n is the current normal stress level, σ_{n0} is the initial normal stress level, K is the spring stiffness and Δz is the deformation of the specimen normal to the interface.

Three different kinds of normal stress boundary conditions can be employed in direct shear tests:

1. <u>Constant normal load test (CNL test):</u> The normal load is constant (K=0, $\Delta z \neq 0$, $d\sigma_n = 0$) similar to drained condition. In this case the interface may compress or dilate freely.

2. Constant volume test (CV test): The volume of soil remains constant ($K = \infty$, $\Delta z = 0$, $d\sigma_n \neq 0$) similar to undrained condition. During this test as no displacement of upper boundary wall is allowed, the normal stress may increase or decrease depending on the tendency of soil to dilate or contract.
3. Constant normal stiffness test (CNS test): The normal load is adjusted by a spring constant to replicate the degradation of normal stress from far field soil (K=constant,$\Delta z \neq 0$,$d\sigma_n \neq 0$).

CNL represents lower bound case where as CV represents upper bound case of CNS test. It has been well established that the pile-soil interface behaviour can be investigated using CNS direct shear tests. Experimental studies have been reported by different researchers on the influence of factors such as initial normal stress, spring stiffness, soil type, relative density, interface surface roughness and magnitude of loading in CNS direct shear apparatus on global specimen response [1−4]. A micro-scale investigation of CNS test results conducted on sand in transparent sided apparatus using PIV analysis showed that the degradation of normal stress in CNS test is due to the contraction and rearrangement of particles occurring in narrow shear band [5]. The aim of this paper is to develop a DEM model to simulate direct shear interface tests and to understand the behaviour of sand-pile interface using these simulations for both static and cyclic tests.

2 SIMULATION PROCEDURE

Two dimensional DEM simulations were carried out using DEM code *PFC*^{2D} [6]. In *PFC*^{2D}, sand particles are modelled as disks of unit thickness and the boundaries are modelled by walls. The interaction between disks (or disk and wall) is determined using contact laws. A typical calculation cycle in *PFC*^{2D} consists of determining forces on disks based on their relative positions using contact laws and updating the position of disk by integration of Newton's second law of motion.

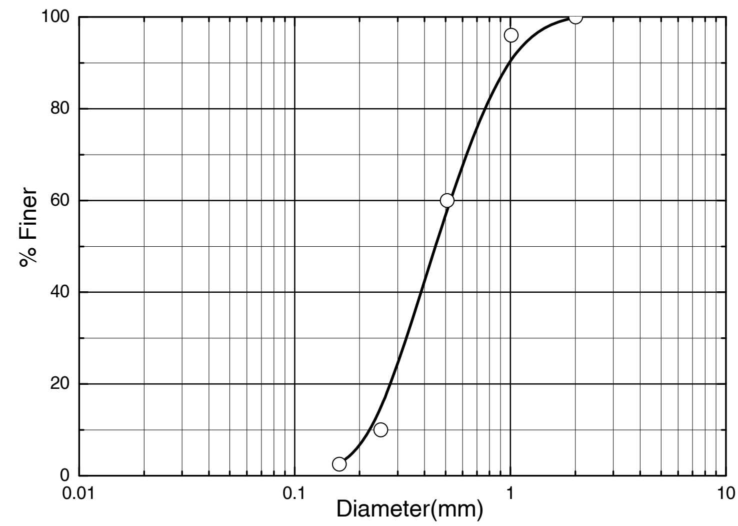

Fig. 1. Grain size distribution curve of modelled sand

For simulations, linear elastic contact law with Coulomb friction was employed with local damping (damping ratio 0.7) to dissipate the excess kinetic energy. Sand modelled was poorly graded quartz sand (Uniformity index U = 2.2; index of curvature C_c=1.0 and mean particle diameter D_{50} = 0.42mm) with grain size distribution as shown in Fig. 1. The dimensions of the interface shear apparatus used in the laboratory was 300 x 300 x 50mm but for simulations, size employed was 180 x 30mm to reduce number of particles and computation time.

Simulation was carried out in three phases:

Phase 1: Side walls and bottom wall with teeth (which represents interface roughness) were constructed. Particles were generated with required grain size distribution by dividing grain size distribution curve in five parts, and were allowed to settle under gravity until equilibrium was achieved. The relative density of generated specimen was found using the following relation [7]:

$$R_d = \frac{0.214 - \eta_{2D}}{0.214 - 0.141} \tag{2}$$

where, R_d is the relative density of the sample and η_{2D} is the porosity achieved at the end of phase 1, 0.214 corresponds to maximum porosity than can be attained at the end of phase 1 for inter-particle coulomb friction coefficient equal to 25 and 0.141 corresponds to the minimum porosity that can be attained at the end of phase 1 for inter-particle coulomb friction coefficient equal to 0.

Phase 2: The top wall is constructed and initial stress conditions are set using servo controlled mechanism.

Phase 3: In this phase, shearing of the sample is carried out. The boundary conditions are maintained as given by equation (1) using servo control mechanism. Fig. 2 shows the schematic diagram of the developed model of CNS test in PFC^{2D} code.

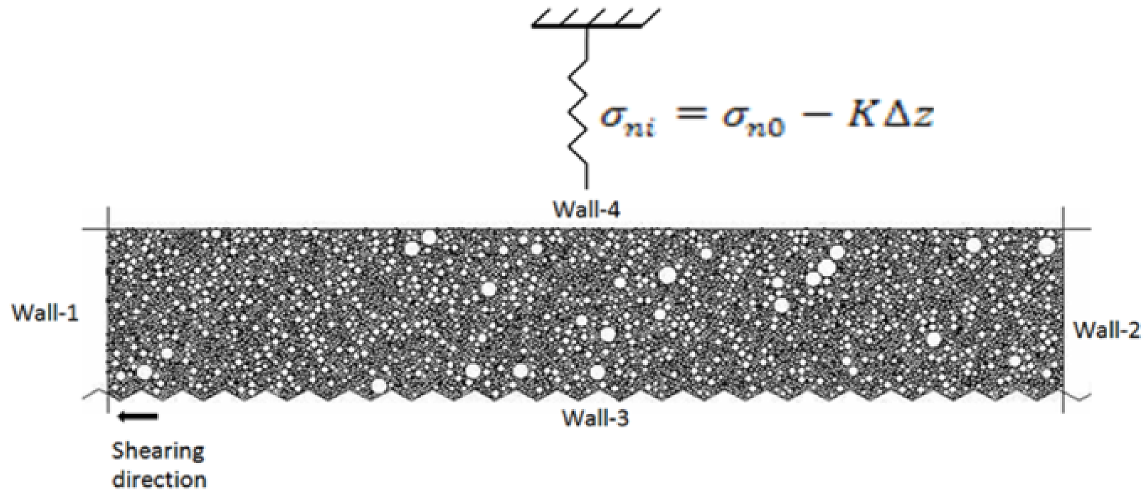

Fig. 2. Schematic diagram of CNS test in PFC^{2D}

3 CALIBRATION

The model was calibrated and validated under both CNL and CNS conditions using appropriate dimensions of interface teeth which approximate roughness of the surface and adjusting appropriate contact law parameters. To set guidelines for calibration, initial simulations were made to understand the influence of teeth parameters and contact law parameters on CNL test.

Increase in tooth height or increase in slope angle (angle made by inclination of tooth with horizontal) causes increase in interface coefficient of friction. Higher slope angle causes high undulations on shear stress-displacement curves due to frequent loss of contact between wall and particles and hence the slope angle should not be kept higher than 30°.

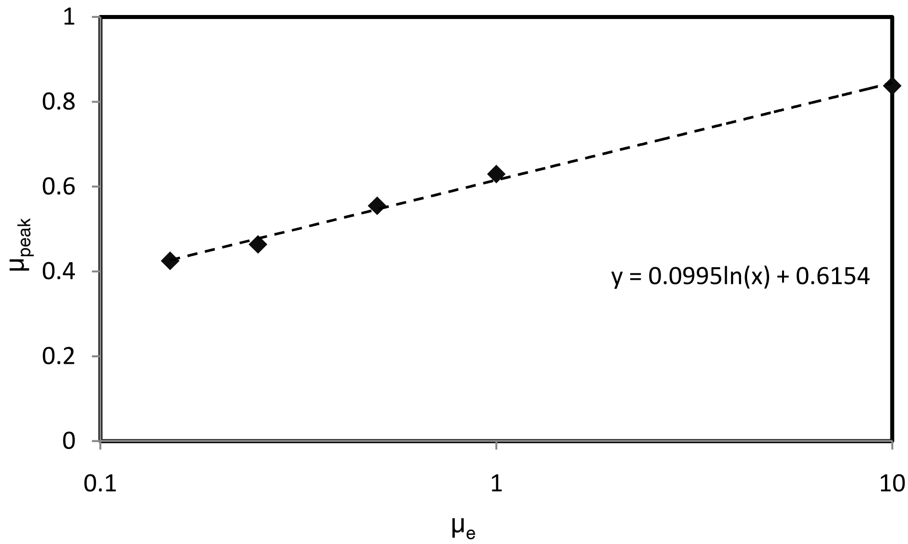

Fig. 3. Relationship between coulomb coefficient of friction and peak interface coefficient of friction

To understand influence of contact parameters for linear elastic contact law viz., normal contact stiffness (K_n), shear contact stiffness (k_s) and inter-particle coulomb friction coefficient (μ_e), simulations were carried out by changing one parameter at a time and keeping the other parameters as constant. It was observed that the increase in μ_e caused increase in peak shear stress while keeping shear modulus and residual shear stress constant. The relation between the inter-particle coulomb friction coefficient (μ_e) and peak interface friction coefficient (μ_{peak}) is shown in Fig. 3. Increase in K_n led to increase in the shear modulus, peak stress values and residual stress values. Change in value of k_s had no influence on shear stress displacement behaviour. Higher μ_e, K_n, and k_s values showed dilatant behaviour in contrast to the contractive behaviour observed for lower values.

The final values of parameters adapted for calibrated model are as shown in Table 1.The model was calibrated and validated with laboratory CNS test data reported for the same sand with 50% relative density [8]. Comparison between results from developed DEM model and experiments are shown in Fig. 4. Comparisons were made for initial normal stress of 100, 200, 300, and 400kPa with spring constants of 48, 120, 96, and 120kPa/mm, respectively.

Good agreement was observed between experimental results and DEM model results for both shear stress and change in normal stress. The results of calibrated model matched consistently at all stress levels.

Table 1. Parameters for calibrated model

Entity	Properties
Balls	Density (ρ) = 2649 kg/m^3 Normal contact stiffness (K_n) = 4x10^6 N/m Shear contact stiffness (K_s) = 2x10^6 N/m Inter particle friction coefficient (μ_e) = 0.17
Walls	Normal contact stiffness (K_n) =1x10^9 N/m Shear contact stiffness (K_s) = 0 N/m Friction coefficient (μ_e) = 0
Interface teeth dimensions	Height of teeth = 1.26mm (3 x D_{50}) Angle of inclination of teeth with horizontal = 30°

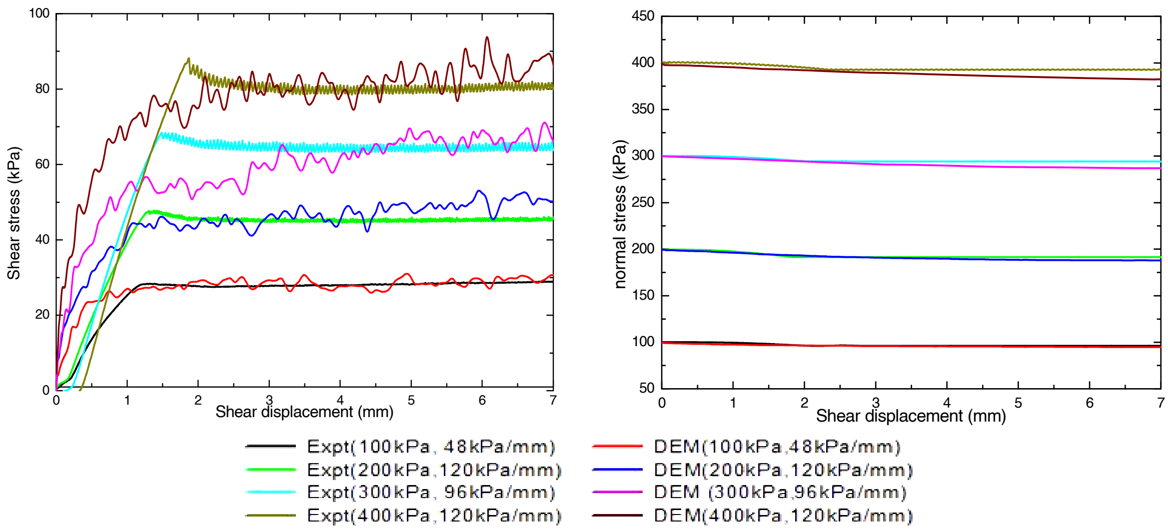

Fig. 4. Comparison between the Calibrated DEM model and laboratory CNS test results

4 RESULTS

Static CNL and static and cyclic CNS tests were carried out for normal stress levels of 100, 200, 300 and 400kPa with spring stiffness values of 88, 184, 288 and 368kPa/mm, respectively. Higher values of K are taken for higher stress level as K is directly proportional to far field small strain shear stiffness [9] in case of pile foundations and this small strain stiffness is found to increase with stress level [10]. All tests were carried out on sand sample with relative density 50% (medium dense sand).

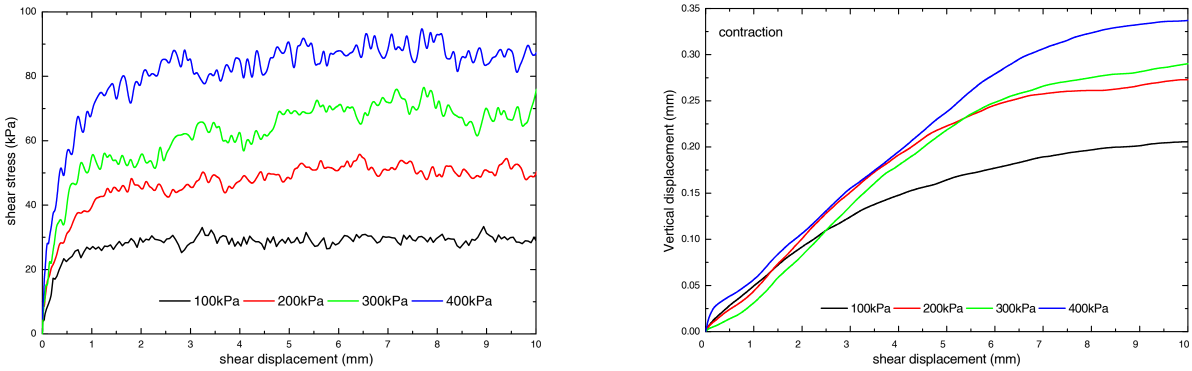

Fig. 5. CNL test results

Results of CNL test are shown in Fig. 5. Contractive behaviour was observed for CNL test and the coefficient of interface friction was found to be 0.233. Figure 6 shows the comparison between static CNL and CNS tests for normal load level of 100kPa, and similar behaviour was observed for other stress levels. No major change in shear stress displacement behaviour was observed but the decrease in normal stress was evident due to imposed CNS condition.

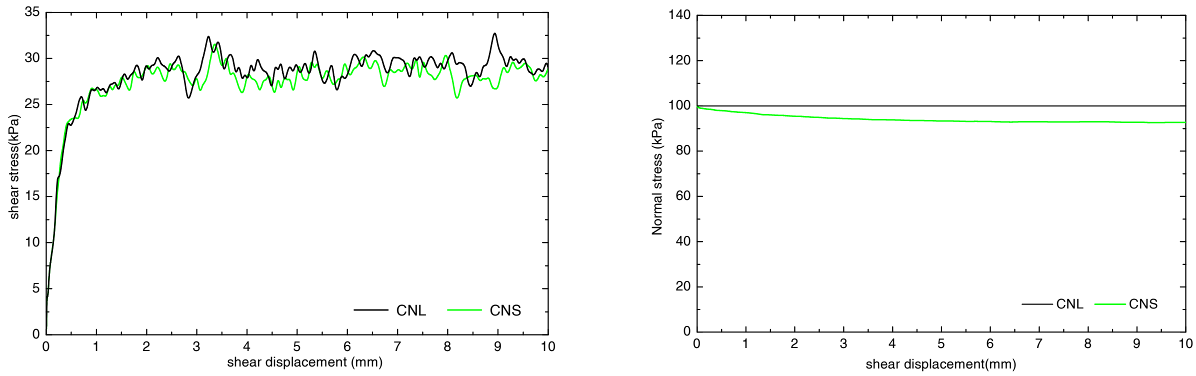

Fig. 6. Comparison between CNL and CNS test results (σ_{no} = 100kPa, K = 88kPa/mm)

Cyclic CNS test simulations were carried out to understand the influence of displacement amplitude. Figure 7 shows degradation factors for maximum shear stress at different stress levels and different displacement amplitudes. Degradation factor is defined as the ratio of soil property under cyclic loading to that under static loading. It was observed for all stress levels that lower displacements (0 to 0.5mm and 0 to 1mm) had less effect on shear stress capacity of the soil, whereas higher displacements (0 to 2mm and 0 to 5mm) resulted in degradation in shear capacity of soil by about 20%. Similar behaviour for different displacement amplitudes has been reported in experimental studies by different researchers [2, 4, 11].

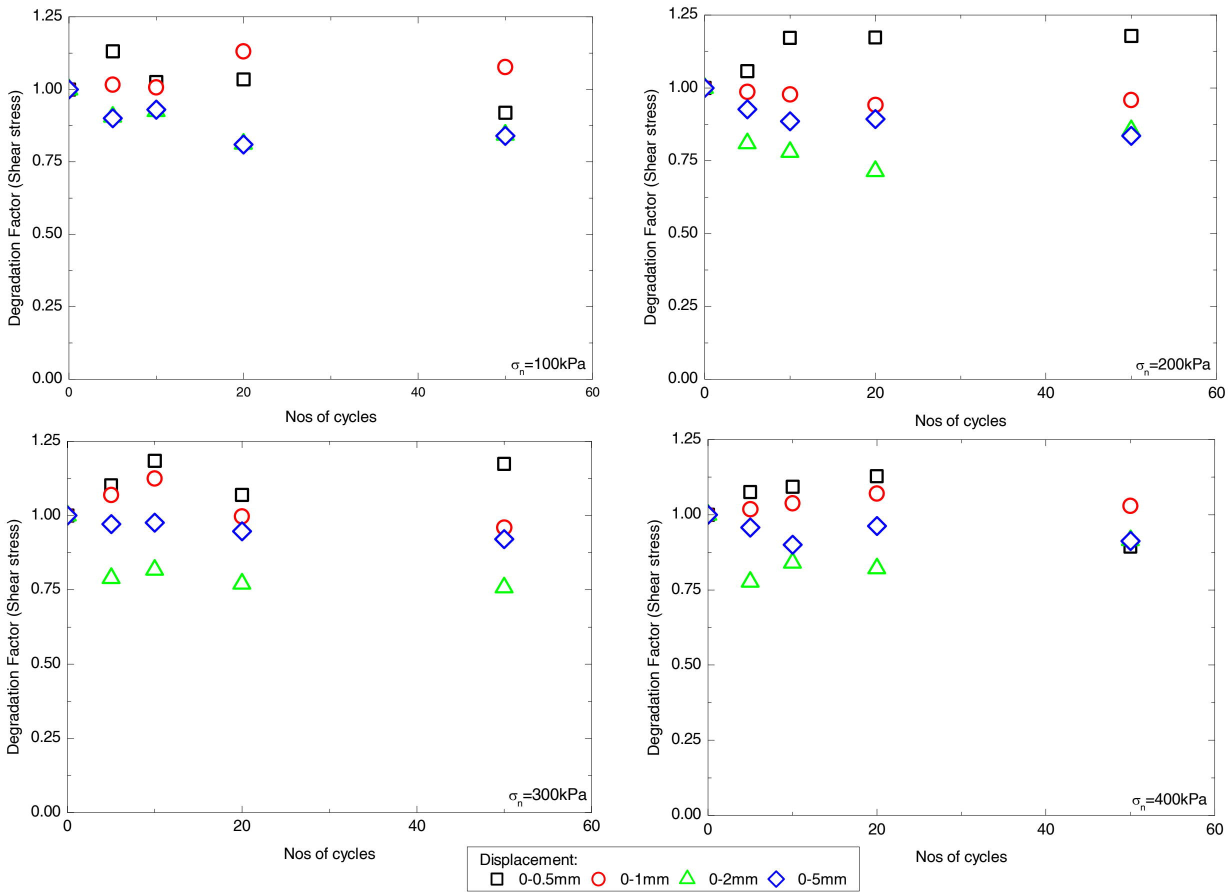

Fig. 7. Degradation factor for cyclic CNS tests with different displacement amplitudes

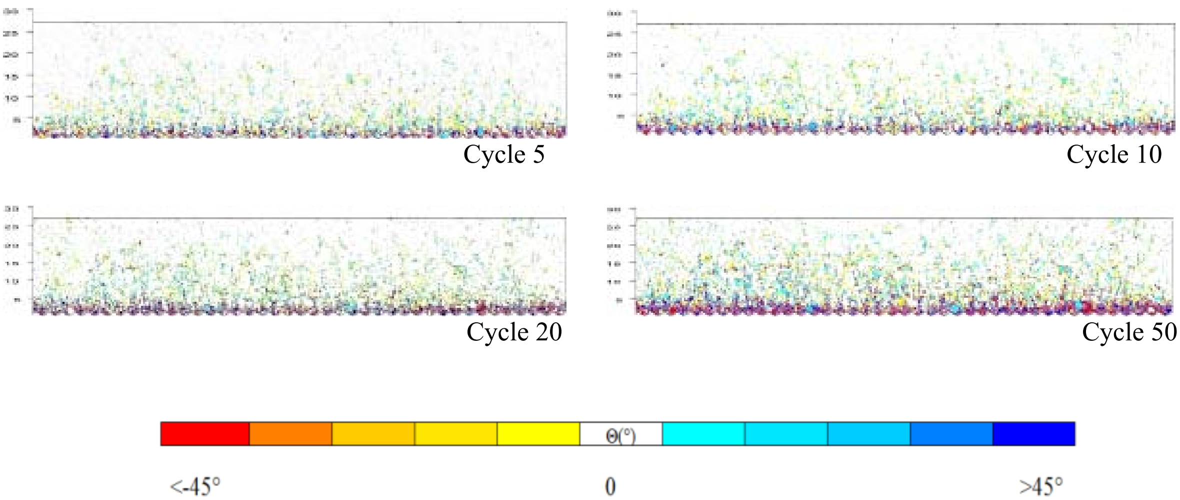

Fig. 8. Development of rotations in cyclic CNS tests. (σ_{no} =100kPa, *K*= 88 kPa/mm, Displacement = 0-2mm)

Rotations of particles can give clear indication of shear band formation [12]. As shearing progresses, higher rotation of the particles is observed near interface due to particle agitation and rearrangement in both static and cyclic tests. Distinct shear band could be observed in the rotation diagrams. Figure 8 shows development of shear band as cycling progresses. The Shear band thickness was found to be dependent on displacement amplitude for cyclic loading. Larger shear band thickness was observed for higher displacement amplitudes. The shear band thickness at the end of all tests for both static and cyclic CNS tests was found to be varying from 5 to 10 times of D_{50}.

5 CONCLUSIONS

DEM simulations were able to reproduce the behaviour of interface direct shear test under different boundary conditions.

Increase in teeth height or teeth slope angle resulted in increase in interface friction. Teeth slope angle should not be greater than 30° for smooth stress displacement curves. Higher inter-particle coulomb friction coefficient resulted in higher peak stresses. K_n affects the overall behaviour of the sample and should be carefully chosen. Larger shear modulus peak stress and residual stresses where observed for higher K_n value. k_s has no effect on stress displacement behaviour. Higher K_n, k_s and inter-particle coulomb friction coefficient resulted in dilatant behaviour in contrast to contractive behaviour for lower values. These points serve as guidelines for calibrating interface direct shear test DEM models.

No major difference was observed between static CNS and CNL tests for shear stress behaviour on sample with relative density of 50%. However, a decrease in normal stress was observed in CNS tests which were evident from the imposed boundary conditions. In cyclic CNS tests, no degradation was observed for lower displacement amplitudes but higher displacement amplitudes led to degradation of shear capacity by about 20%. Shear band thickness was measured from rotation diagrams and was observed to be 5 to 10 times D_{50} for all the tests. Thicker shear band was observed for higher displacement amplitudes.

ACKNOWLEDGEMENTS

First author have received a scholarship from German Academic Exchange Service DAAD to carry out this work at Institute for Geotechnical Engineering, Leibniz University of Hannover, Germany. Their support is gratefully acknowledged.

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